

NASA TECHNICAL NOTE



NASA TN D-4016

*c.1*

LOAN COPY: RETURN  
AFRL (WHL-2)  
KILLAM AFB, NM

0130817



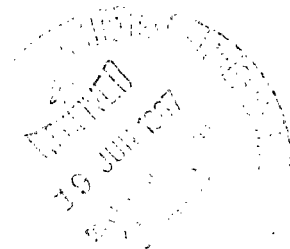
TECH LIBRARY KAFB, NM

NASA TN D-4016

UNIAXIAL AND BIAXIAL FRACTURE TOUGHNESS  
OF EXTRA-LOW-INTERSTITIAL  
5A1-2.5Sn TITANIUM ALLOY SHEET AT 20° K

*by Timothy L. Sullivan*

*Lewis Research Center  
Cleveland, Ohio*





0130817

NASA TN D-4016

UNIAXIAL AND BIAXIAL FRACTURE TOUGHNESS OF EXTRA-LOW-  
INTERSTITIAL 5Al-2.5Sn TITANIUM ALLOY SHEET AT 20° K

By Timothy L. Sullivan

Lewis Research Center  
Cleveland, Ohio

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

---

For sale by the Clearinghouse for Federal Scientific and Technical Information  
Springfield, Virginia 22151 - CFSTI price \$3.00

# UNIAXIAL AND BIAXIAL FRACTURE TOUGHNESS OF EXTRA-LOW-INTERSTITIAL 5Al-2.5Sn TITANIUM ALLOY SHEET AT 20° K

by Timothy L. Sullivan

Lewis Research Center

## SUMMARY

An experimental investigation was conducted to determine the effect of sheet width and notch length on the calculated fracture toughness values of 0.020-inch-thick (0.051 cm) extra-low-interstitial (ELI) grade of the titanium alloy Ti-5Al-2.5Sn at 20° K. Through-the-thickness center notches ranging in length from 1/8 inch (0.32 cm) to one-third of the specimen width were placed in specimens 3, 6, and 12 inches (7.6, 15.2, and 30.5 cm) wide. Sharp notches were obtained by electrical discharge machining and low-stress fatiguing to the desired length. Critical crack length was measured with the NASA continuity gage. The Griffith-Irwin theory was used to calculate the fracture toughness values.

Tests of specimens with notches 1 inch (2.5 cm) long or longer in all three sheet widths produced nearly constant values of fracture toughness. Tests of specimens with shorter notch lengths produced higher fracture toughness values, the use of which could result in unconservative designs. By neglecting the Irwin plastic zone correction term, nearly constant nominal fracture toughness values were obtained from specimens with notches as small as 1/4 inch (0.64 cm).

A correlation between flat sheet and through-cracked cylindrical pressure vessels is included which shows good agreement with experimental data. The notched pressure vessels are compared on the basis of strength to density ratio with similar pressure vessels fabricated from 2014-T6 aluminum.

## INTRODUCTION

The use of liquid hydrogen as a propellant for the upper stages of launch vehicles necessitates large volume tanks because of the low density of liquid hydrogen. Fabrication of propellant tanks with materials of high strength to density ratios can result in a

considerable reduction in weight and, therefore, enhance payload capabilities. However, many high-strength materials lose much of their toughness at cryogenic temperatures and, hence, much of their strength in the presence of cracks or other flaws. Because it is important for the designer to know the behavior of a material in the presence of a flaw, a program was undertaken at the Lewis Research Center to determine the fracture toughness properties of a number of high-strength alloys. The results of an investigation of the fracture toughness of 2014-T6 aluminum at  $77^{\circ}\text{K}$  ( $-320^{\circ}\text{F}$ ) are given in reference 1. Another alloy that combines a high strength to density ratio with moderate toughness at  $20^{\circ}\text{K}$  ( $-423^{\circ}\text{F}$ ) is the extra-low-interstitial (ELI) grade of the titanium alloy, Ti-5Al-2.5Sn. Therefore, 0.020-inch-thick (0.051 cm) Ti-5Al-2.5Sn ELI was tested both in flat-sheet form and as cylindrical pressure vessels at this temperature.

The Griffith-Irwin analysis of the behavior of a structure in the presence of a flaw (ref. 2) relates the fracture load to the size of the crack, the geometry of the structure, the yield strength of the material, and a single material fracture toughness parameter. An analysis of the strength of longitudinally through-cracked cylindrical pressure vessels, which includes the increase in stress intensity due to bulging around the crack, is given in reference 3. Use of either of these analyses is based on the plane stress fracture toughness,  $K_{\text{Ic}}$ .

For reasons of economics and the physical limitations of cryogenic testing facilities, it is desirable in materials testing to use a minimum size specimen. If this principle is to be applied to fracture toughness testing, it is necessary to determine how  $K_{\text{Ic}}$  is affected by sheet width. The present work examines the effect of varying the specimen width and initial crack length on  $K_{\text{Ic}}$  in Ti-5Al-2.5Sn ELI at  $20^{\circ}\text{K}$ . Data from reference 3 are used to compare strength to density ratios for notched Ti-5Al-2.5Sn ELI and 2014-T6 Al pressure vessels. A correlation between Ti-5Al-2.5Sn ELI flat-sheet data and pressure-vessel data at  $20^{\circ}\text{K}$  is included.

## ANALYTICAL PROCEDURE

The procedure used in the fabrication and testing of specimens and in calculating the fracture toughness values follows the recommendations of the American Society for Testing and Materials' Special Committee on Fracture Testing of High Strength Materials (ref. 4). Fracture toughness values were calculated by using the Irwin modified Griffith theory that takes into account finite specimen width and plastic flow at the notch tip. From reference 5,

$$K_c = \sigma_c \sqrt{W \tan \left[ \frac{\pi}{W} \left( a_c + \frac{1}{2\pi} \frac{K_c^2}{\sigma_{ys}^2} \right) \right]} \quad (1)$$

where  $K_c$  is the fracture toughness,  $\sigma_c$  the gross fracture stress,  $W$  the specimen width,  $a_c$  the critical half-crack length, and  $\sigma_{ys}$  the 0.2 percent yield strength of the material. For calculation of valid  $K_c$  values, the ASTM recommends that the net fracture stress not exceed 0.80 times the yield strength.

A nominal fracture toughness  $K_{cn}$  based on the initial half-crack length  $a_o$  can be calculated when the critical crack length is not known or when it is desired to compare toughness values based on initial crack length with those based on critical crack length. The equation for  $K_{cn}$  is given by

$$K_{cn} = \sigma_c \sqrt{W \tan \left[ \frac{\pi}{W} \left( a_o + \frac{1}{2\pi} \frac{K_{cn}^2}{\sigma_{ys}^2} \right) \right]} \quad (2)$$

where  $a_o$  is the initial half-crack length.

## EXPERIMENTAL PROCEDURE

### Specimen Preparation and Testing

All the specimens were fabricated from a single heat of Ti-5Al-2.5Sn ELI sheet nominally 0.020 inch (0.05 cm) thick. The material was mill annealed at 558° K (1325° F) for 4 hours and furnace cooled. The chemical analysis of this heat as furnished by the material supplier is given in the following table:

Composition, wt %							
C	Fe	N <sub>2</sub>	Al	H <sub>2</sub>	O <sub>2</sub>	Sn	Mn
0.022	0.08	0.014	5.1	0.006 to 0.009	0.08	2.5	<0.006

Smooth specimens (fig. 1) were tested at 20°, 77°, and 294° K (room temperature) to determine the conventional tensile properties of the material. Fracture toughness values were obtained at 20° K from through-center-cracked specimens 3, 6, and 12 inches (7.6, 15.2, and 30.5 cm) wide (fig. 2). All the specimens were fabricated so

that the loading direction was parallel to the rolling direction of the sheet. Screening tests had shown only a slight variation (less than 5 percent) in the properties obtained from specimens fabricated with the loading direction perpendicular to the rolling direction compared with those loaded parallel to the rolling direction. Following fabrication, the specimens were stress relieved by heating to  $867^{\circ}\text{K}$  ( $1100^{\circ}\text{F}$ ) for 2 hours.

Sharp notches were obtained by electrical discharge machining of a through-central slot and low-stress fatiguing the slot to the desired notch length. For notches 0.5 inch (1.3 cm) long and longer, the slot was extended 0.1 inch (0.25 cm) at each end. The shorter notches were extended approximately one-fourth of their final length at each end. The maximum net stress used in fatigue crack extension ranged from approximately 20 percent of room-temperature yield strength for the longer notches to approximately 30 percent for the shorter notch lengths. Notch lengths ranged from  $1/8$  inch (0.32 cm) to one-third of the width of the specimen.

The 3- and 6-inch-wide (7.6 and 15.2 cm) specimens, except for the  $1/8$ -inch-notch (0.32 cm), 6-inch-wide (15.2 cm) specimens, were loaded to failure in a 20 000-pound-capacity (89 000 N) hydraulically actuated testing machine. The  $1/8$ -inch-notch (0.32 cm), 6-inch-wide (15.2 cm) specimens and all the 12-inch-wide (30.5 cm) specimens were loaded to failure in a 400 000-pound-capacity (1 780 000 N) screw-actuated testing machine. The desired cryogenic temperature was obtained by immersing the specimen in liquid hydrogen ( $20^{\circ}\text{K}$ ). The 400 000-pound (1 780 000 N) testing machine and cryostat are shown in figure 3(a). A cross section of the cryostat is shown in figure 3(b).

Buckling of the test specimens while under load was a possibility due to a combination of the light gage of the material and the difference in the transverse strains at the notch and away from the notch. In order to prevent out-of-plane buckling, a fixture was applied to the surface of the 6- and 12-inch-wide (15.2 and 30.5 cm) sheet in all tests where the notch length exceeded 1 inch (2.5 cm). The fixture was also used on the 3-inch-wide (7.6 cm) specimens containing notches  $1/2$  and 1 inch (1.3 and 2.5 cm) in length. The fixture prevented buckling but did not restrain the specimen in the plane of the sheet. It is shown applied to a 12-inch-wide (30.5 cm) specimen in figure 4.

## Measurement of Critical Crack Length

The stable crack growth, which took place while loading the specimen to failure, was measured with the NASA continuity gage (ref. 6). The continuity gage is a multiple-element foil gage that is mounted on the surface of a specimen at the crack tip, perpendicular to the expected direction of crack growth. The gage elements are connected in parallel so that as the growing crack breaks an element, a finite resistance change takes place, which can be monitored on appropriate readout equipment. A load cell signal is

recorded simultaneously. Satisfactory operation of the continuity gage is contingent upon the use of proper mounting procedures, and, in some cases, a calibration is necessary for accurate interpretation of the gage output. For a more detailed description of gage operation, use, and calibration procedures, the reader is referred to reference 6.

In figure 5, a typical oscillograph trace of the continuity gage and load cell outputs is shown for a test at 20° K. The crack growth was of a discontinuous nature. From points A to B, the crack grew through four elements of gage 1 while growing through seven elements of gage 2 (points A' to B'). Because the gage elements are 0.01 inch (0.025 cm) apart, the gages indicate that the crack grew approximately 0.11 inch (0.28 cm) before arresting. The lines BC and B'C' indicate no additional crack growth until the points C and C' were reached where the specimen failed. From the start of crack growth to point B, eight elements had broken in gage 1, and to B' thirteen elements had broken in gage 2. Hence the total stable crack growth was 0.21 inch (0.53 cm). For an initial notch length of 1 inch (2.5 cm), a critical crack length of 1.21 inches (3.07 cm) would be used to compute  $K_{Ic}$ . The growth at AB, A'B' was accompanied by a slight drop in load, which may account for the arrest of the crack growth. This crack growth behavior would indicate that fracture toughness test results are dependent on testing machine stiffness, an area deserving of further investigation.

## RESULTS AND DISCUSSION

The conventional tensile properties of the Ti-5Al-2.5Sn ELI sheet used in this investigation are listed in table I. Tests were conducted at 20°, 77°, and 294° K. Included are the 0.2 percent yield strength, ultimate strength, and modulus of elasticity.

### Fracture Toughness Determination

The notch test results are listed in table II. In most cases three specimens were tested at each condition. In figure 6(a), values of  $K_{Ic}$  calculated by using equation (1) are plotted as a function of the critical crack length  $2a_c$ . In tests where the crack length was less than 1/2 inch (1.3 cm), the net fracture stress generally exceeded 0.80 times the yield strength. Therefore, the values of  $K_{Ic}$  obtained from specimens with initial notches of nominally 1/8 and 1/4 inch (0.32 and 0.64 cm) are not included in figure 6. Despite the data scatter, it is apparent that the values of  $K_{Ic}$  are increasing with decreasing crack length. In figure 6(b), the same test results are used to calculate values of  $K_{Ic}$  neglecting the Irwin plastic zone correction,  $(K_{Ic}/\sigma_{ys})^2/2\pi$ . The same trend

is apparent but the rate at which  $K_c$  increases with decreasing crack length is not as great.

In figure 7(a), nominal fracture toughness  $K_{cn}$  is plotted as a function of the initial crack length  $2a_o$ . For all three specimen widths,  $K_{cn}$  reaches a value of approximately  $94 \times 10^3 \text{ psi } \sqrt{\text{in.}}$  ( $103 \times 10^3 \text{ (N/cm}^2\text{) } \sqrt{\text{cm}}$ ) when the initial crack length approaches one-third of the specimen width ( $2a_o/W \rightarrow 1/3$ ). At an initial notch length of about 0.25 inch (0.64 cm)  $K_{cn}$  reaches a peak value for all three widths. In figure 7(b), values of  $K_{cn}$  obtained by neglecting the plastic zone correction are plotted. Here, the values are nearly constant for all three widths and for initial notch lengths ranging from 0.25 inch (0.64 cm) to one-third of the specimen width (net stresses as high as about  $0.80 \sigma_{ys}$ ). The two sets of data shown in figure 7 indicate that, for initial notch lengths of less than 1 inch (2.5 cm) (net stresses greater than about  $0.45 \sigma_{ys}$ ), equation (2) overcorrects for plasticity effects. However, other investigations (refs. 1 and 4) have found the plastic zone correction term to work properly for net stresses as high as  $0.80 \sigma_{ys}$ .

If the value  $K_{cn}$  reaches as  $2a_o/W$  approaches  $1/3$  is taken as the "true" value of  $K_{cn}$  and used in equation (2) to predict the critical fracture stress for other specimen width and notch length combinations, the curves shown in figure 8 result. Here,  $K_{cn}$  was taken to be  $94 \times 10^3 \text{ psi } \sqrt{\text{in.}}$  ( $103 \times 10^3 \text{ (N/cm}^2\text{) } \sqrt{\text{cm}}$ ) and curves drawn for 3-, 6-, and 12-inch-wide (7.62, 15.2, and 30.5 cm) specimens. The agreement between the predicted and experimental values of critical stress is good except for the shorter notches where the predicted underestimates the experimental fracture stress. In figure 9, the same curves are drawn by using  $K_c$  and the critical crack length  $2a_c$ , and applying equation (1). The "true"  $K_c$  was taken as  $103 \times 10^3 \text{ psi } \sqrt{\text{in.}}$  ( $113 \times 10^3 \text{ (N/cm}^2\text{) } \sqrt{\text{cm}}$ ), the average  $K_c$  obtained from specimens with  $2a_o/W = 1/3$ . Again the agreement between predicted and experimental values of critical stress is good for specimens with initial notch lengths of 1 inch (2.5 cm) or longer. For shorter initial notch lengths, the predicted value of critical stress is less than that obtained experimentally and thus is conservative. The true  $K_c$  exceeds the true  $K_{cn}$  by about 10 percent. Hence, use of  $K_{cn}$  instead of  $K_c$  would result in a conservative design and, for many applications, would be quite suitable. Conversely, improper use of  $K_c$  values by assuming the initial and critical crack lengths to be equal would produce unconservative results.

## Pressure Vessel Material Strength to Density Ratio Comparison

In reference 3, an expression was derived for predicting the fracture stress of through-cracked, cylindrical pressure vessels. The expression takes into account the increase in stress intensity due to bulging around the crack with a bulge coefficient  $C$ . This expression states that



$$\sigma_{hc} = \frac{K_{cn}}{\sqrt{\pi a_o + \frac{1}{2} \frac{K_{cn}^2}{\sigma_{yb}^2} \left(1 + C \frac{a_o}{R}\right)}} \quad (3)$$

where  $\sigma_{hc}$  is the critical hoop stress,  $\sigma_{yb}$  the biaxial yield strength in a 1 to 2 stress field, and  $R$  the cylinder radius ( $K_{cn}$  and  $a_o$  were defined previously). In order to compare various materials on the basis on their strength to density ratio, equation (3) can be written as

$$\frac{\sigma_{hc}}{\rho} = \frac{\frac{K_{cn}}{\rho}}{\sqrt{\pi a_o + \frac{1}{2} \frac{K_{cn}^2}{\sigma_{yb}^2} \left(1 + C \frac{a_o}{R}\right)}} \quad (4)$$

where  $\rho$  is the material density. In figure 10, strength to density ratios for pressure vessels with initial notches of up to 2.0 inches (5.1 cm) are compared for 0.020-inch (0.051 cm) Ti-5Al-2.5Sn ELI and 0.060-inch (0.15 cm) 2014-T6 Al at 20° K. Because of the texture strengthening exhibited by the titanium alloy,  $\sigma_{yb}$  was obtained from a single pressure vessel burst test. For the aluminum alloy,  $\sigma_{yb}$  was taken as 1.15 times the uniaxial yield strength. The data, bulge coefficient  $C$ , and  $K_{cn}$  values were obtained from reference 3. Because no antibuckling device was used, the  $K_{cn}$  value reported in reference 3 is about 7.5 percent lower than the value obtained in this investigation. The correlation between the flat-sheet and pressure-vessel data using equation (4) shows good agreement with the experimental data and indicates that the analytical expression adequately takes into account the increase in stress intensity due to bulging around a crack. Comparing the curves for Ti-5Al-2.5Sn ELI and 2014-T6 Al shows the titanium alloy to be superior on the basis of strength to density ratio for the range of initial notch lengths investigated.

## CONCLUSIONS

Nearly constant values of fracture toughness  $K_c$  and nominal fracture toughness  $K_{cn}$  in 0.020-inch (0.051 cm) Ti-5Al-2.5Sn ELI sheet were obtained at 20° K from specimens 3, 6, and 12 inches (7.62, 15.2, and 30.5 cm) wide where the crack length to

specimen width ratio was 1/3. However, when shorter crack lengths were tested the toughness values calculated by using the Griffith-Irwin equation increased as the net fracture stress to yield strength ratio increased from about 0.45. By neglecting the Irwin plastic zone correction term, nearly constant values of nominal fracture toughness were obtained for net to yield strength ratios up to 0.80.

While use of the Irwin plastic zone correction term has yielded satisfactory results with some materials, using it with 0.020 inch (0.051 cm) Ti-5Al-2.5Sn ELI sheet at 20° K could result in the calculation of unconservative toughness values and consequently lead to unsafe designs.

Lewis Research Center,  
National Aeronautics and Space Administration,  
Cleveland, Ohio, February 10, 1967,  
124-08-08-19-22.

## REFERENCES

1. Orange, Thomas W.: Fracture Toughness of Wide 2014-T6 Aluminum Sheet at 320° F. NASA TN D- , 1967.
2. Irwin, G. R.: Fracture. Handbuch der Physik. Vol. VI., S. Flugge, ed., Springer-Verlag (Berlin), 1958, pp. 551-590.
3. Anderson, Robert B.; and Sullivan, Timothy L.: Fracture Mechanics of Through-Cracked Cylindrical Pressure Vessels. NASA TN D-3252, 1966.
4. ASTM Special Committee on Fracture Testing of High-Strength Materials: Progress in Measuring Fracture Toughness and Using Fracture Mechanics. Materials Res. Standards, vol. 4, no. 3, Mar. 1964, pp. 107-119.
5. ASTM Special Committee on Fracture Toughness Testing of High-Strength Metallic Materials: Fracture Testing of High-Strength Sheet Materials. Part I. ASTM Bulletin, no. 243, Jan. 1960, pp. 29-40.
6. Sullivan, Timothy L.; and Orange, Thomas W.: Continuity Gage Measurement of Crack Growth on Flat and Curved Surfaces at Cryogenic Temperatures. NASA TN D-3747, 1966.

TABLE I. - Ti-5Al-2.5Sn ELI TENSILE TEST DATA

(a) U. S. customary units

Temperature, °F	0.2 Percent yield strength, psi	Ultimate strength, psi	Modulus of elasticity, psi
-423	$203.7 \times 10^3$	$224.2 \times 10^3$	$17.8 \times 10^6$
	203.4	224.3	17.3
	198.0	225.3	17.1
	203.1	224.1	17.6
	207.2	228.7	18.1
	205.3	226.7	18.1
	Average	$203.5 \times 10^3$	$225.6 \times 10^3$
-320	$172.3 \times 10^3$	$179.9 \times 10^3$	$18.2 \times 10^6$
	170.6	177.9	18.1
	174.6	182.2	17.8
	173.3	180.8	18.2
	173.0	179.9	18.2
	Average	$172.8 \times 10^3$	$180.3 \times 10^3$
70	$104.4 \times 10^3$	$109.9 \times 10^3$	$16.4 \times 10^6$
	106.0	111.1	16.5
	104.3	109.2	16.1
	104.4	110.4	15.7
	104.8	110.0	16.4
	105.6	110.2	16.3
	Average	$104.9 \times 10^3$	$110.1 \times 10^3$

(b) Metric units

Temperature, °K	0.2 Percent yield strength, N/cm <sup>2</sup>	Ultimate strength, N/cm <sup>2</sup>	Modulus of elasticity, N/cm <sup>2</sup>
20	$140.3 \times 10^3$	$154.5 \times 10^3$	$12.3 \times 10^6$
	140.1	154.5	11.9
	136.4	155.2	11.8
	139.9	154.4	12.1
	142.8	157.6	12.5
	141.5	156.2	12.5
	Average	$140.3 \times 10^3$	$155.6 \times 10^3$
77	$118.7 \times 10^3$	$124.0 \times 10^3$	$12.5 \times 10^6$
	117.5	122.6	12.5
	120.3	125.5	12.3
	119.4	124.6	12.5
	119.2	124.0	12.5
	Average	$119.1 \times 10^3$	$124.3 \times 10^3$
294	$71.9 \times 10^3$	$75.7 \times 10^3$	$11.3 \times 10^6$
	73.0	76.5	11.4
	71.9	75.2	11.1
	71.9	76.1	10.8
	72.2	75.8	11.3
	72.8	75.9	11.2
	Average	$72.3 \times 10^3$	$75.9 \times 10^3$

TABLE II. - Ti-5Al-2.5Sn ELI FRACTURE TOUGHNESS TEST DATA

(a) -423° F; U.S. customary units

Specimen width, W, in.	Specimen thickness, in.	Gross fracture stress, $\sigma_c$ , psi	Initial crack length, $2a_0$ , in.	Notch to yield strength ratio	Nominal fracture toughness, $K_{cn}$ , psi $\sqrt{\text{in.}}$		Critical crack length, $2a_c$ , in.	Net to yield strength ratio	Fracture toughness, $K_c$ , psi $\sqrt{\text{in.}}$	
					Plastic zone correction included	Plastic zone correction neglected			Plastic zone correction included	Plastic zone correction neglected
12.00	0.0202	39.2 $\times 10^3$	4.00	0.289	104.3 $\times 10^3$	103.2 $\times 10^3$	4.04	0.290	105.0 $\times 10^3$	103.8 $\times 10^3$
	.0196	35.2	4.02	.260	93.9	92.9	4.35	.271	98.6	97.6
	.0192	35.4	4.00	.261	94.2	93.2	4.45	.277	100.7	99.5
	.0187	52.1	2.00	.307	95.0	93.4	2.41	.320	104.9	103.1
	.0188	51.2	2.00	.302	93.3	91.8	2.46	.317	104.2	102.4
	.0206	51.6	2.00	.304	94.1	92.5	2.33	.315	102.1	100.3
	.0183	76.0	.98	.407	98.4	94.6	1.19	.415	108.4	104.3
	.0208	70.9	.99	.380	91.6	88.7	1.37	.393	108.0	104.6
	.0187	71.3	1.00	.382	92.6	89.6	1.17	.388	98.0	97.0
	.0181	103.6	.50	.531	98.5	91.9	.69	.540	115.8	108.0
	.0177	104.3	.49	.534	98.3	91.6	.62	.541	110.6	103.0
	.0191	108.6	.49	.556	103.0	95.3	.66	.565	119.7	110.7
	.0209	151.3	.24	.759	108.8	92.9	.40	.769	141.2	120.0
	.0177	154.4	.24	.774	113.3	94.8	.65	.802	185.5	156.2
	.0198	153.2	.24	.768	112.1	94.1	.47	.784	155.7	131.7
	.0201	183.9	.12	.913	104.6	79.8	.26	.924	152.9	117.5
	.0199	181.1	.12	.899	100.3	78.6	.31	.914	162.8	126.4
	.0192	178.4	.13	.886	101.1	80.6	.38	.905	175.9	137.9
6.00	0.0181	49.0 $\times 10^3$	2.01	0.362	93.7 $\times 10^3$	91.5 $\times 10^3$	2.23	0.383	99.8 $\times 10^3$	97.6 $\times 10^3$
	.0183	48.8	2.00	.360	92.7	90.8	2.42	.402	104.9	102.5
	.0175	50.1	2.00	.369	95.3	93.2	2.39	.409	106.9	104.3
	.0190	74.1	1.00	.437	97.1	94.0	1.34	.469	114.3	109.8
	.0189	71.4	1.02	.423	94.7	91.5	1.21	.440	103.8	100.1
	.0185	73.7	1.00	.435	96.4	93.4	1.33	.465	113.1	108.8
	.0185	110.5	.49	.591	104.5	97.2	.64	.608	120.8	111.3
	.0176	105.9	.49	.567	99.9	93.2	.80	.600	129.1	119.6
	.0187	109.1	.50	.585	104.5	97.0	.72	.609	126.6	116.7
	.0187	156.4	.24	.801	115.1	96.1	.64	.860	189.4	157.6
	.0188	157.2	.25	.806	118.3	98.6	.61	.860	186.0	154.5
	.0187	153.3	.25	.786	113.3	96.1	.53	.826	166.7	140.3
	.0185	191.9	.13	.964	106.1	86.7	.22	.979	151.8	112.9
	.0184	181.6	.13	.912	105.9	82.1	.25	.931	147.2	113.9
3.00	0.0190	69.3 $\times 10^3$	1.00	0.512	95.0 $\times 10^3$	91.1 $\times 10^3$	1.24	0.581	109.9 $\times 10^3$	104.5 $\times 10^3$
	.0199	68.6	1.03	.514	95.8	91.9	1.28	.589	111.3	105.7
	.0194	72.2	1.02	.538	100.6	96.1	1.24	.606	115.0	108.9
	.0194	69.0	1.04	.519	97.0	93.0	1.30	.598	113.3	107.5
	.0190	103.6	.54	.621	104.4	96.5	.81	.697	131.7	120.3
	.0184	110.1	.50	.649	107.7	98.6	(a)	-----	-----	-----
	.0188	107.6	.51	.637	105.9	97.5	.73	.698	129.5	118.1
	.0196	138.9	.27	.749	103.5	90.2	.47	.809	139.6	120.6
	.0187	127.9	.34	.708	105.1	93.7	.67	.809	153.0	134.0
	.0187	129.9	.32	.714	103.5	91.9	.50	.766	132.0	116.5
	.0198	172.7	.15	.892	103.8	82.8	.33	.954	158.6	125.0
	.0193	165.4	.15	.856	98.8	80.6	.27	.893	133.1	108.1
	.0193	181.0	.12	.925	99.7	77.3	.20	.953	131.6	101.6

<sup>a</sup>Questionable crack growth data.

TABLE II. - Concluded. Ti-5Al-2.5Sn ELI FRACTURE TOUGHNESS TEST DATA

(b) 20° K; metric units

Specimen width, W, cm	Specimen thickness, cm	Gross fracture stress, $\sigma_c$ , N/cm <sup>2</sup>	Initial crack length, 2a <sub>o</sub> , cm	Notch to yield strength ratio	Nominal fracture toughness, K <sub>cn</sub> , (N/cm <sup>2</sup> ) <sup>1/2</sup> cm		Critical crack length, 2a <sub>c</sub> , cm	Net to yield strength ratio	Fracture toughness, K <sub>c</sub> , (N/cm <sup>2</sup> ) <sup>1/2</sup> cm	
					Plastic zone correction included	Plastic zone correction neglected			Plastic zone correction included	Plastic zone correction neglected
30.5	0.0513	27.0×10 <sup>3</sup>	10.16	0.289	114.6×10 <sup>3</sup>	113.4×10 <sup>3</sup>	10.26	0.290	115.4×10 <sup>3</sup>	114.1×10 <sup>3</sup>
	.0498	24.3	10.21	.260	103.2	102.1	11.05	.271	108.4	107.3
	.0488	24.4	10.16	.261	103.5	102.4	11.30	.277	110.7	109.4
	.0475	35.9	5.08	.307	104.4	102.6	6.12	.320	115.3	113.3
	.0478	35.3	5.08	.302	102.5	100.9	6.25	.317	114.5	112.5
	.0523	35.6	5.08	.304	103.4	101.7	5.92	.315	112.2	110.2
	.0465	52.4	2.49	.407	108.1	104.0	3.02	.415	119.1	114.7
	.0528	48.9	2.51	.380	100.7	97.5	3.48	.393	118.7	115.0
	.0475	49.2	2.54	.382	101.8	98.5	2.97	.388	107.7	106.6
	.0460	71.4	1.27	.531	108.3	101.0	1.75	.540	127.3	118.7
	.0450	71.9	1.24	.534	108.0	100.7	1.57	.541	121.5	113.2
	.0485	74.9	1.24	.556	113.2	104.7	1.68	.565	131.6	121.7
	.0531	104.3	.61	.759	119.6	102.1	1.02	.769	155.2	131.9
	.0450	106.5	.61	.774	124.5	104.2	1.65	.802	204.0	171.7
	.0503	105.6	.61	.769	123.2	103.4	1.19	.784	171.2	144.8
	.0511	126.8	.30	.913	115.0	87.8	.66	.924	168.1	129.2
	.0505	124.9	.30	.899	110.2	86.4	.79	.914	179.0	138.9
	.0488	123.0	.33	.886	111.1	88.6	.97	.905	193.4	151.6
15.2	0.0460	33.8×10 <sup>3</sup>	5.11	0.362	103.0×10 <sup>3</sup>	100.6×10 <sup>3</sup>	5.66	0.383	109.7×10 <sup>3</sup>	107.3×10 <sup>3</sup>
	.0465	33.6	5.08	.360	101.9	99.8	6.15	.402	115.3	112.7
	.0444	34.5	5.08	.369	104.7	102.4	6.07	.409	117.5	114.6
	.0483	51.1	2.54	.437	106.7	103.3	3.40	.469	125.6	120.7
	.0480	49.2	2.59	.423	104.1	100.6	3.07	.440	114.1	110.0
	.0470	50.8	2.54	.435	105.9	102.6	3.38	.465	124.3	119.6
	.0470	76.2	1.24	.591	114.8	106.8	1.63	.608	132.8	122.3
	.0447	73.0	1.24	.567	109.8	102.4	2.03	.600	141.9	131.5
	.0475	75.2	1.27	.585	114.8	106.6	1.83	.609	139.1	128.3
	.0475	107.8	.61	.801	126.5	105.6	1.63	.860	208.1	173.3
	.0478	108.4	.64	.806	130.0	108.4	1.55	.860	204.4	169.9
	.0475	105.7	.64	.786	124.5	105.6	1.35	.826	183.3	154.2
	.0470	132.3	.33	.964	116.6	95.3	.56	.979	166.9	124.1
	.0467	125.2	.33	.912	116.4	90.2	.64	.931	161.8	125.2
7.6	0.0483	47.8×10 <sup>3</sup>	2.54	0.512	104.5×10 <sup>3</sup>	100.2×10 <sup>3</sup>	3.15	0.581	120.9×10 <sup>3</sup>	115.0×10 <sup>3</sup>
	.0505	47.3	2.62	.514	105.4	101.1	3.25	.589	122.4	116.3
	.0493	49.8	2.59	.538	110.7	105.7	3.15	.606	126.5	119.8
	.0493	47.6	2.64	.519	106.7	102.3	3.30	.598	124.6	118.3
	.0483	71.4	1.37	.621	114.8	106.2	2.06	.697	144.9	132.3
	.0467	75.9	1.27	.649	118.5	108.5	(a)	-----	-----	-----
	.0478	74.2	1.30	.637	116.5	107.3	1.85	.698	142.5	129.9
	.0498	95.8	.68	.749	113.7	99.1	1.19	.809	153.5	132.6
	.0475	88.2	.86	.708	115.5	103.0	1.70	.809	168.2	147.3
	.0475	89.6	.80	.714	113.7	101.0	1.27	.766	145.1	128.1
	.0503	119.1	.37	.892	114.1	91.0	.84	.954	174.4	137.4
	.0490	114.0	.38	.856	108.6	88.6	.69	.893	146.3	118.8
	.0490	124.8	.30	.925	109.6	84.9	.51	.953	144.7	111.7

<sup>a</sup>Questionable crack growth data.

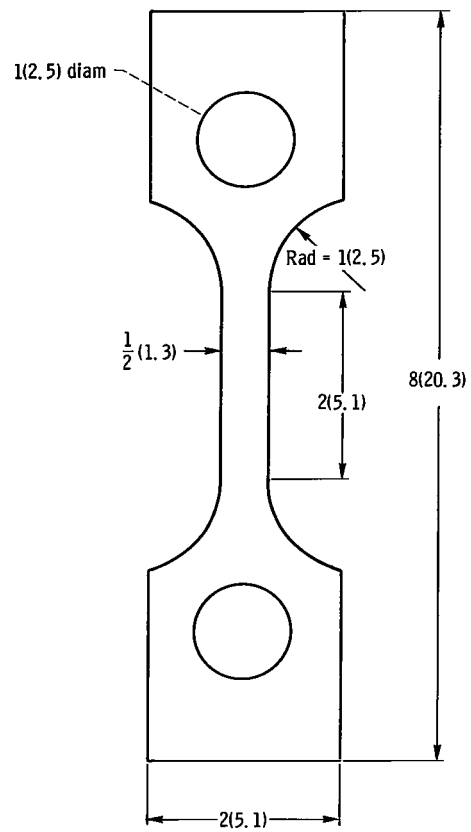


Figure 1. - Smooth thin-sheet tensile specimen.  
(All dimensions are in inches (cm).)

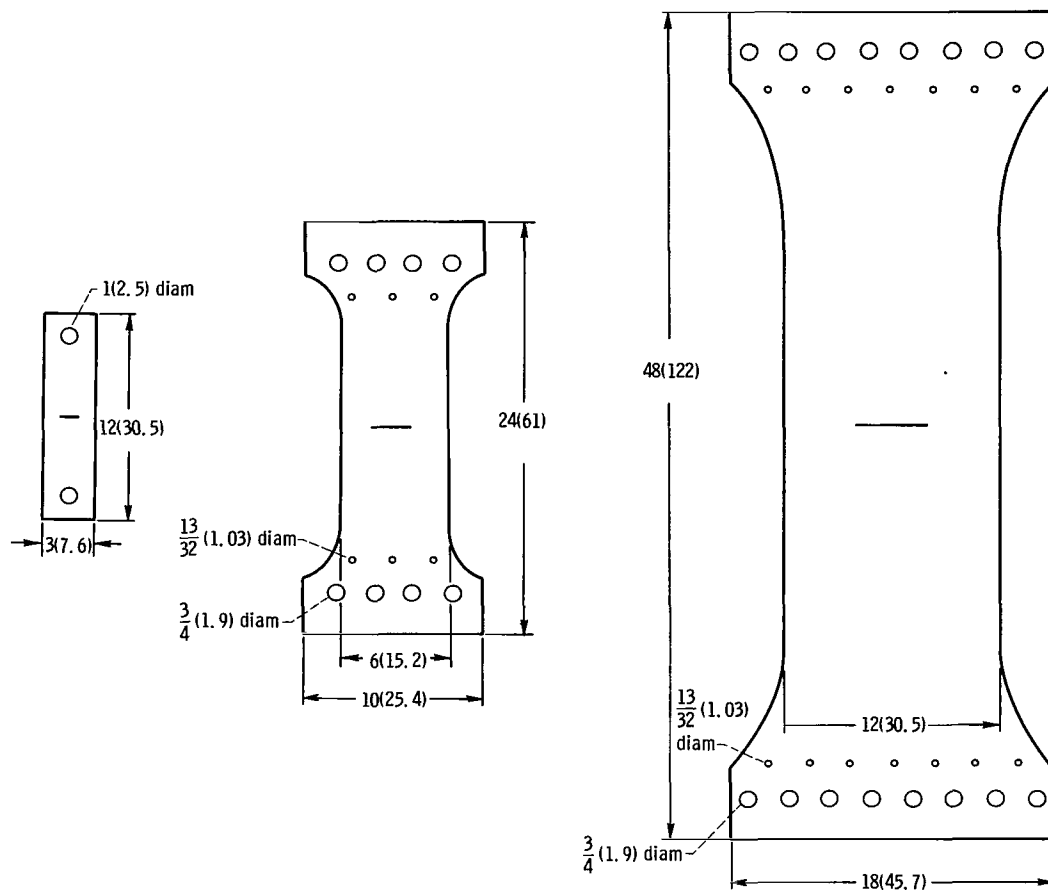
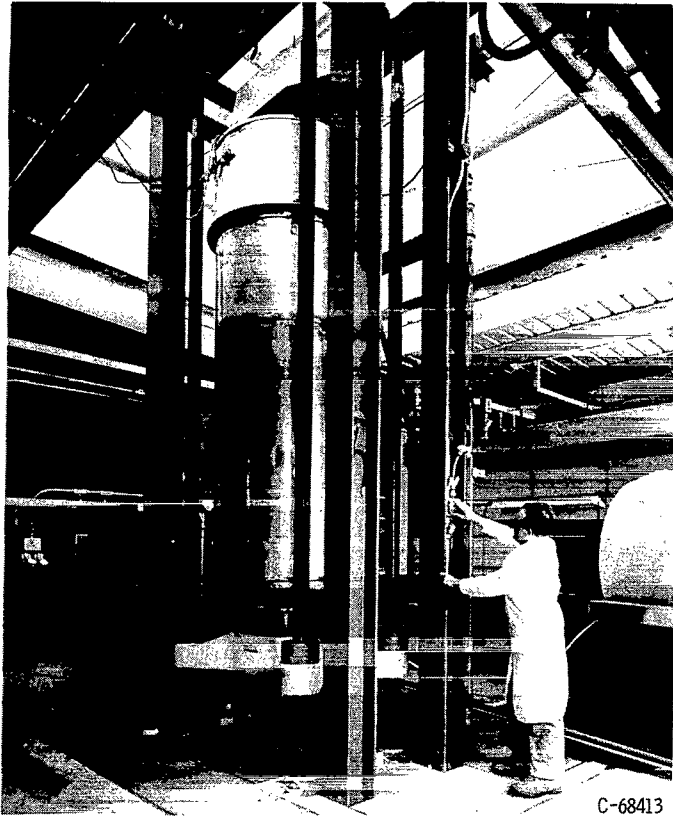
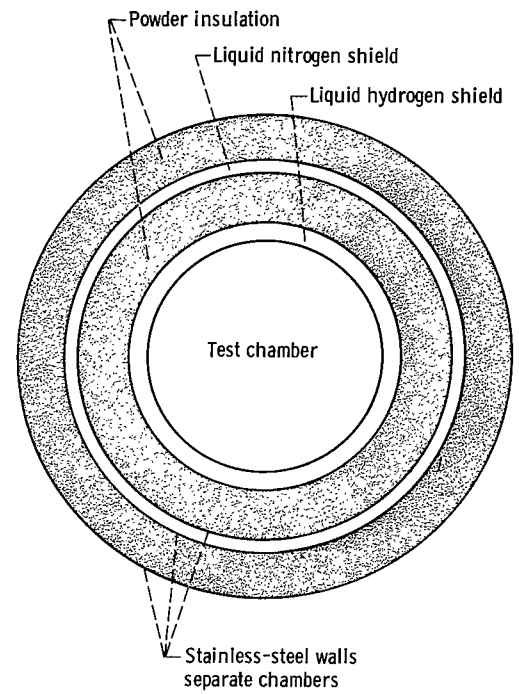


Figure 2. - Fracture toughness specimens 3, 6, and 12 inches (7.6, 15.2, and 30.5 cm) wide. (All dimensions are in inches (cm).)



C-68413

(a) Machine and cryostat.



(b) Cross section of cryostat.

Figure 3. - Tensile testing facility, 400 000-pound (178 000 N) capacity.



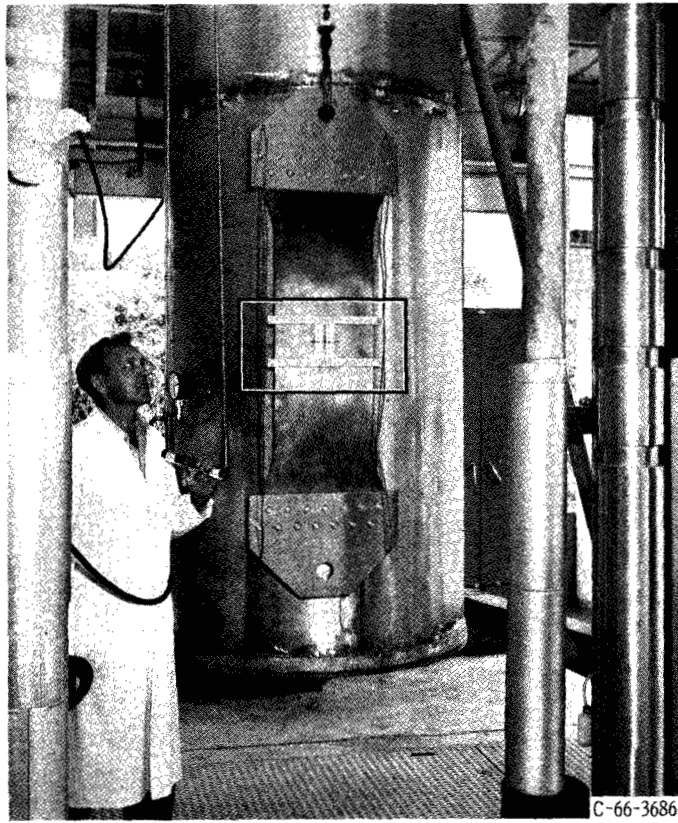
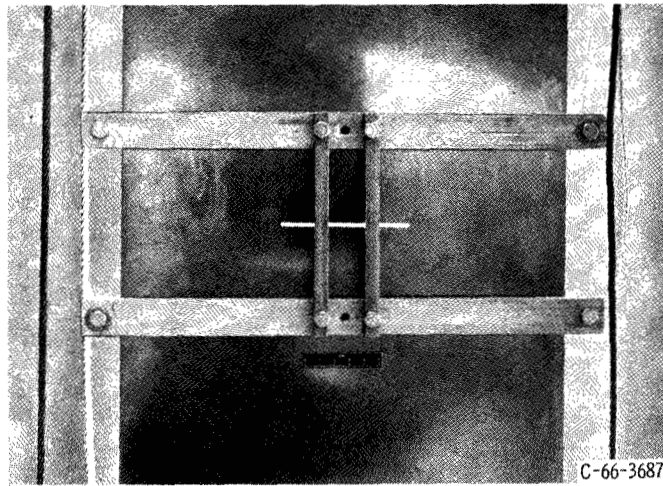


Figure 4. - Sheet specimen 12 inches (30.5 cm) wide with antibuckling fixture attached.

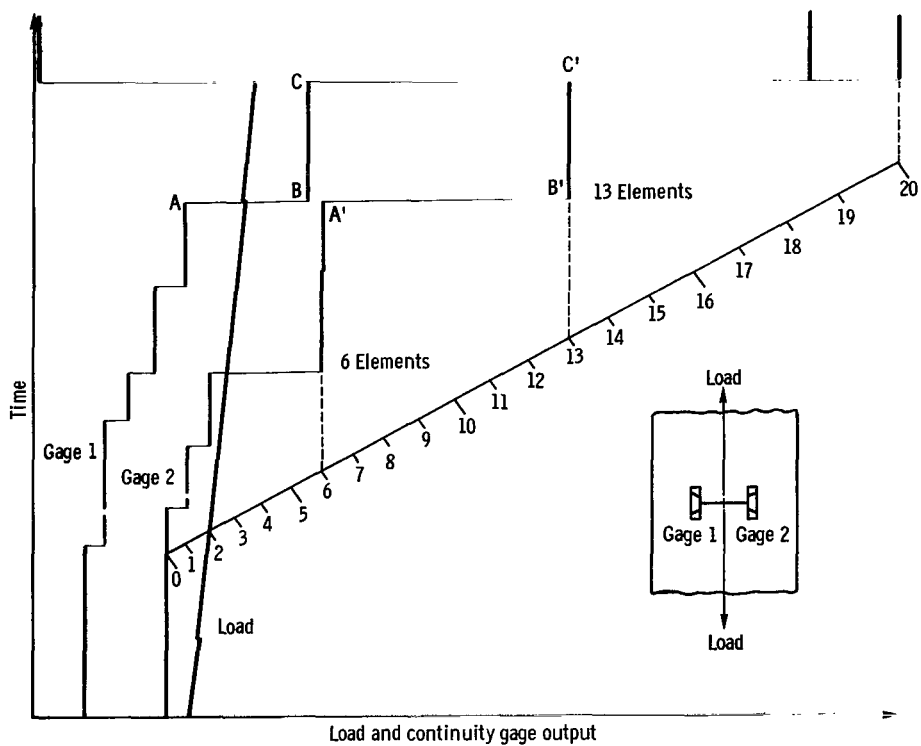


Figure 5. - Typical continuity gage oscillograph trace.

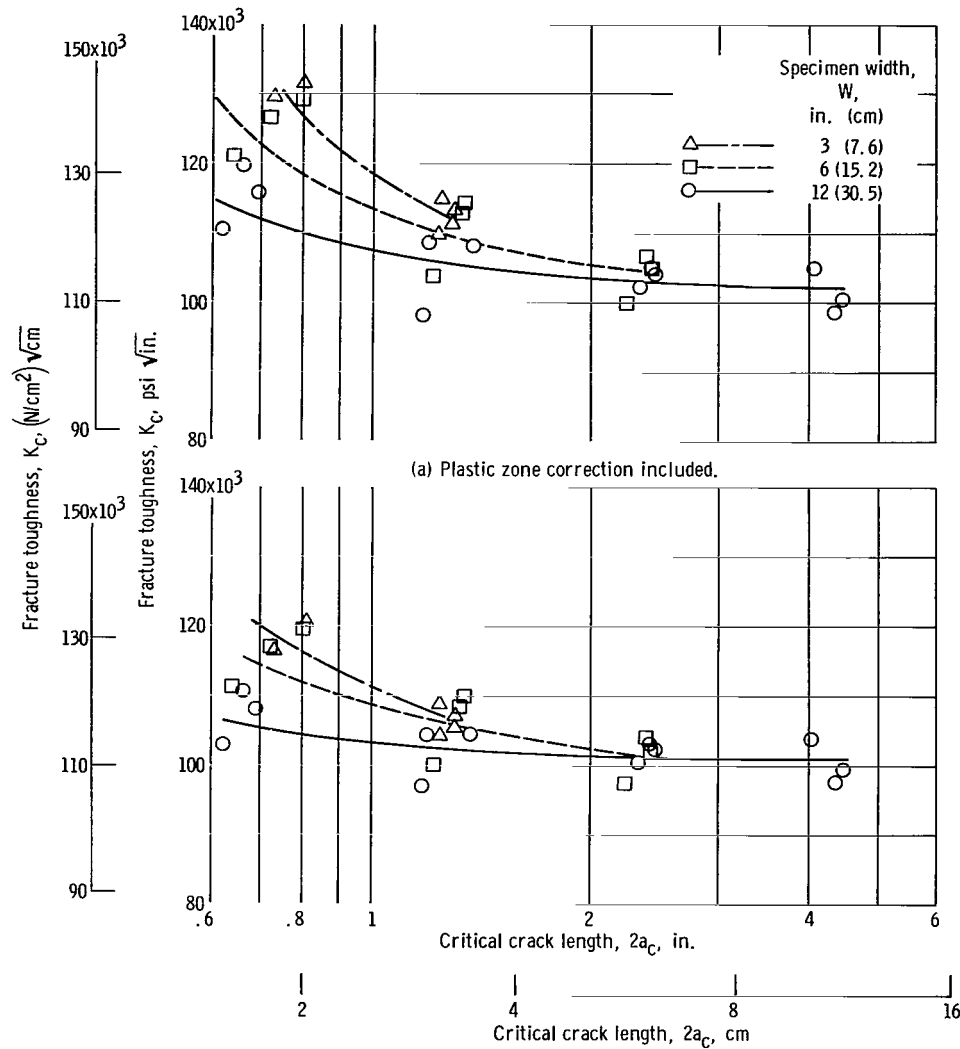


Figure 6. - Plane stress fracture toughness as function of critical crack length for Ti-5Al-2.5Sn ELI at 20° K. Yield strength at 20° K, 203 500 psi ( $140 \times 10^3$  N/cm<sup>2</sup>); net stress less than 0.80 times yield strength.

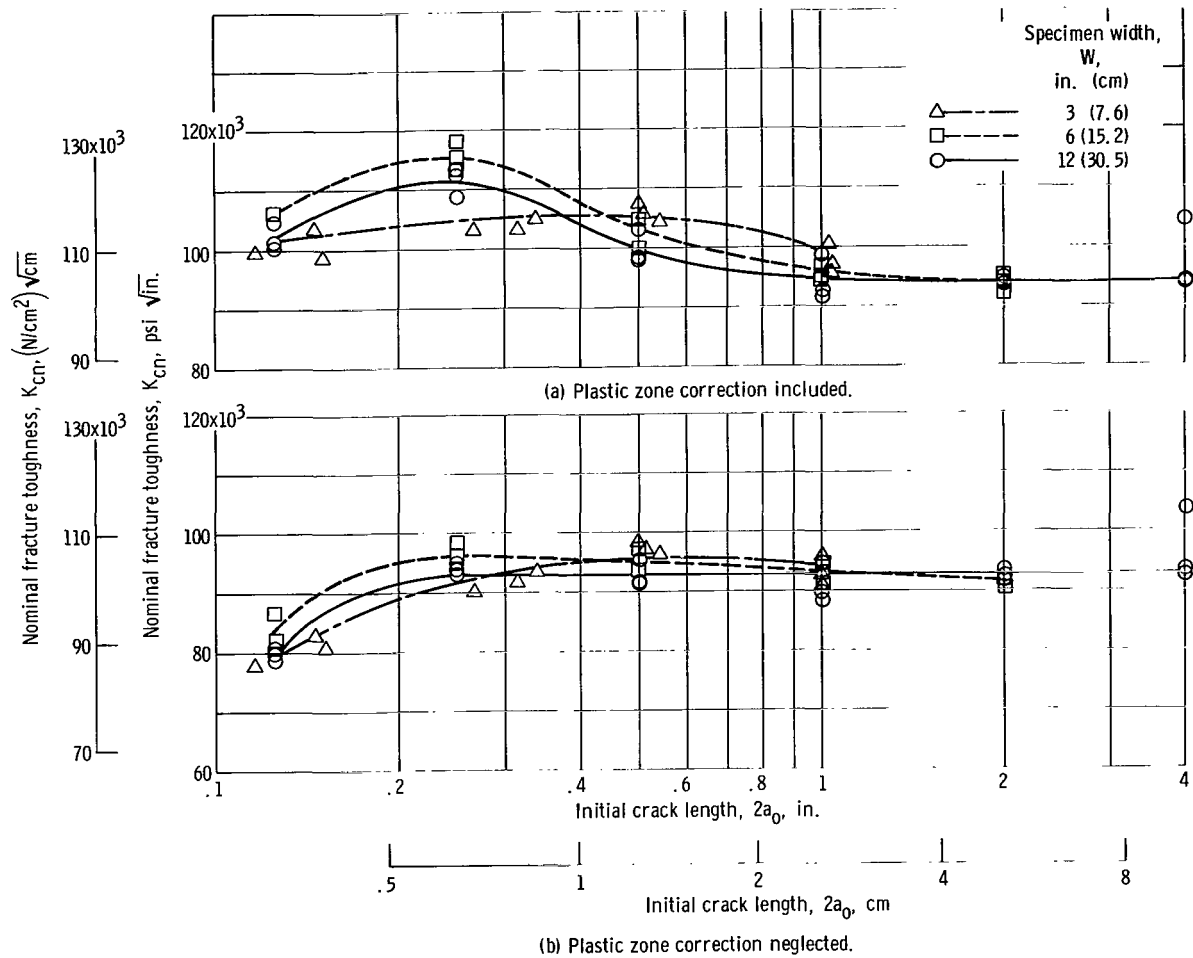


Figure 7. - Nominal fracture toughness as function of initial crack length for Ti-5Al-2.5Sn ELI at 20° K. Yield strength at 20° K, 203 500 psi (140x10<sup>3</sup> N/cm<sup>2</sup>).

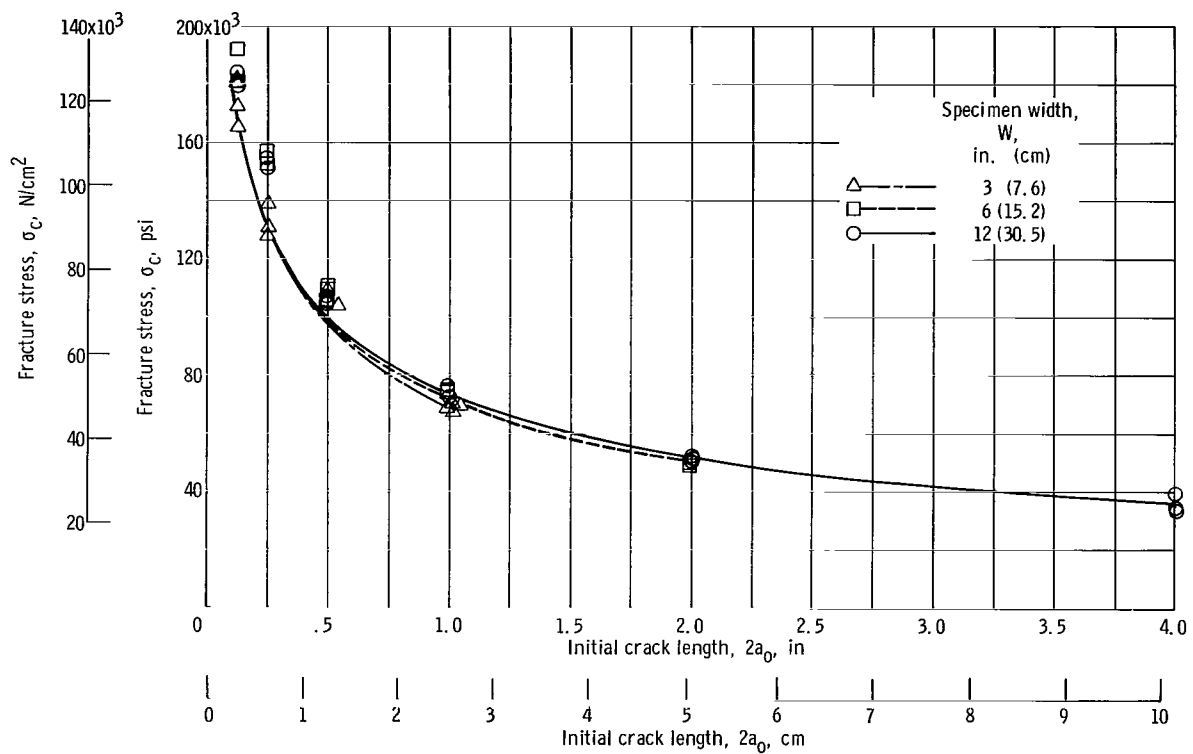


Figure 8. - Critical fracture stress as function of initial crack length for Ti-5Al-2.5Sn ELI at 20° K. Nominal fracture toughness,  $94 \times 10^3 \text{ psi } \sqrt{\text{in.}}$  ( $103 \times 10^3 \text{ (N/cm}^2\text{)} \sqrt{\text{cm}}$ ).

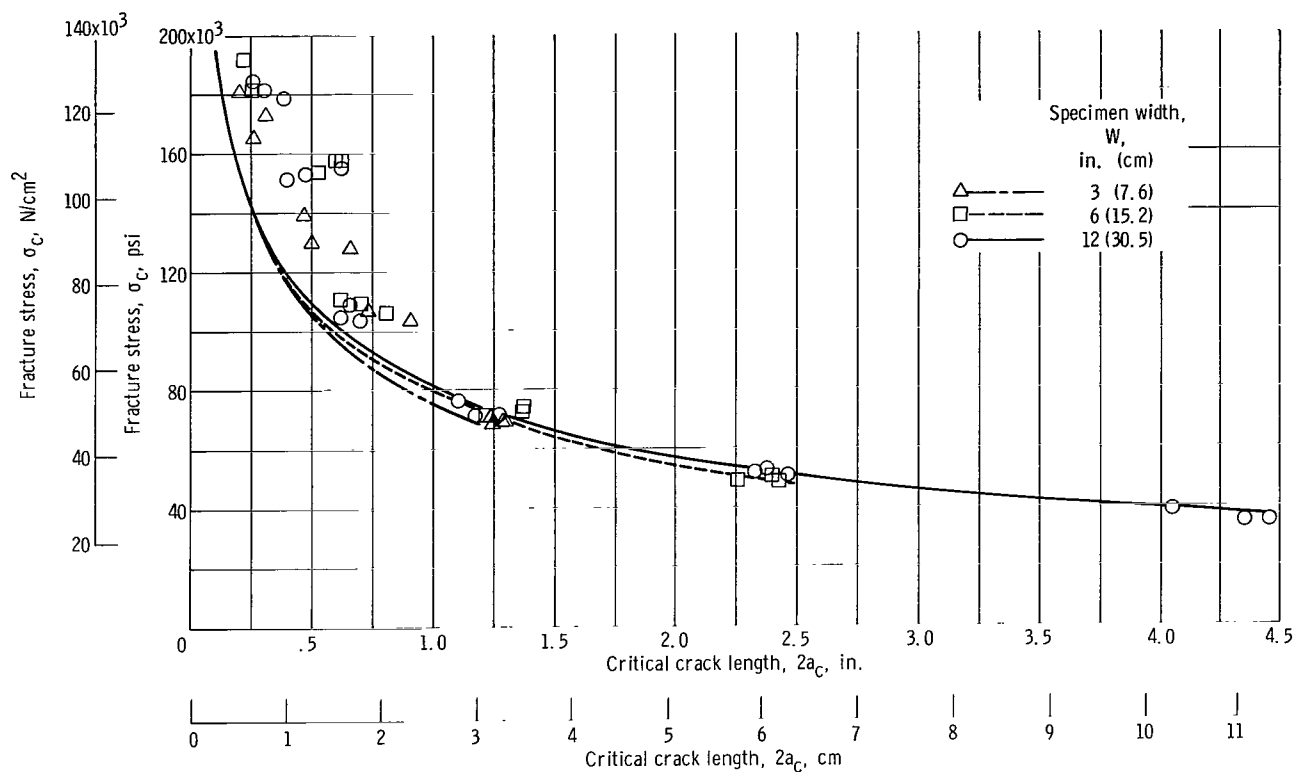


Figure 9. - Critical fracture stress as function of critical crack length for Ti-5Al-2.5Sn ELI at 20° K. Fracture toughness,  $103 \times 10^3$  psi  $\sqrt{\text{in.}}$  ( $113 \times 10^3$  (N/cm<sup>2</sup>)  $\sqrt{\text{cm}}$ ).

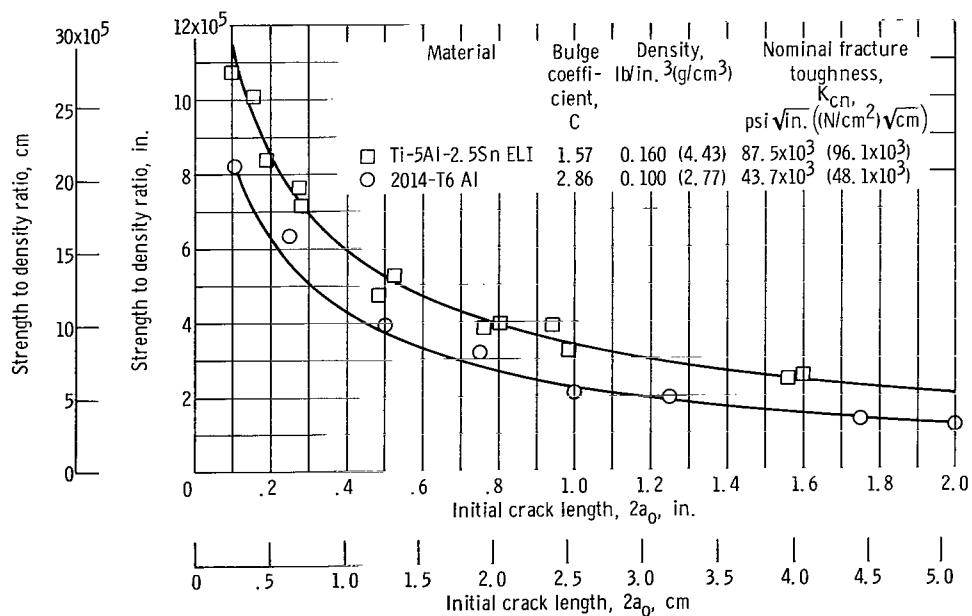


Figure 10. - Comparison of strength to density ratios of notched pressure vessels at 20° K.

*"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."*

—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

## NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

**TECHNICAL REPORTS:** Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge.

**TECHNICAL NOTES:** Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

**TECHNICAL MEMORANDUMS:** Information receiving limited distribution because of preliminary data, security classification, or other reasons.

**CONTRACTOR REPORTS:** Scientific and technical information generated under a NASA contract or grant and considered an important contribution to existing knowledge.

**TECHNICAL TRANSLATIONS:** Information published in a foreign language considered to merit NASA distribution in English.

**SPECIAL PUBLICATIONS:** Information derived from or of value to NASA activities. Publications include conference proceedings, monographs, data compilations, handbooks, sourcebooks, and special bibliographies.

**TECHNOLOGY UTILIZATION PUBLICATIONS:** Information on technology used by NASA that may be of particular interest in commercial and other non-aerospace applications. Publications include Tech Briefs, Technology Utilization Reports and Notes, and Technology Surveys.

*Details on the availability of these publications may be obtained from:*

SCIENTIFIC AND TECHNICAL INFORMATION DIVISION  
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION  
Washington, D.C. 20546